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U.S. Department of Energy Wind Turbine Development Projects

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U.S. DEPARTMENT OF ENERGY WIND TURBINE DEVELOPMENT PROJECTS

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ABSTRACT: This paper provides an overview of wind-turbine development activities in the Unites States and relates those activities to market conditions and projections. Several factors are responsible for a surge in wind energy development in the United States, including a federal production tax credit, "green power" marketing, and improving cost and reliability. More development is likely, as approximately 363 GW of new capacity will be needed by 2020 to meet growing demand and replace retiring units. The U.S. Department of Energy (DOE) is helping two companies develop next-generation turbines intended to generate electricity for $0.025/kWh or less. We expect to achieve this objective through a combination of improved engineering methods and configuration advancements. This should ensure that wind power will compete effectively against advanced combined-cycle plants having projected generating costs of $0.031/kWh in 2005. To address the market for small and intermediate-size wind turbines, DOE is assisting five companies in their attempts to develop new turbines having low capital cost and high reliability. Additional information regarding U.S. wind energy programs is available on the internet site www.nrel.gov/wind/. E-mail addresses for the turbine manufacturers are found in the Acknowledgements.
KEYWORDS: Wind Turbines (HAWT) - R&D - Cost of Energy

1. INTRODUCTION

The U.S. Department of Energy (DOE) is working in partnerships with industry to develop improved wind turbine technologies that will help expand the use of wind energy worldwide. These partnerships are carried out under the Turbine Research element of the Wind Energy Systems Program, which has supported the emergence of new wind turbines and associated components and subsystems since its inception in 1990. This paper provides an overview of the current activities in DOE's Turbine Research element, and relates those activities to current market conditions and projections for electricity sales, generating prices, and capacity.

1.1 U.S. Market Situation

The United States is currently experiencing its largest surge in utility-scale wind energy development since the 1980s. New wind power plants totaling more than 200 MW began operation in 1998, and another 600 MW is projected to be on-line before 2000. This wave of growth is also expanding into new regions of the country with immense wind power potential.

The recent wind power plant construction follows several years of stagnation and uncertainty regarding the prospects for wind energy in the United States The emerging deregulation of the electric utility sector has slowed construction of new generating capacity since the mid-1990s. Another contributing factor is that prevailing energy costs in the United States are among the lowest in the world. In bids for new projects, the cost of proposed generation will be balanced against the utilities' avoided cost, which typically ranges from $0.015 to $0.03/kWh. Transition to a more competitive market structure for electricity generation is expected to further increase the emphasis on low energy costs.

A modest federal subsidy, the Production Tax Credit (PTC), valued at approximately $0.017/kWh, has been available since 1994 to encourage wind development. However, wind-generated electricity costs only recently fell to the point where the PTC provided the compelling financial incentive needed to move a large number of wind projects forward. The expiration of the PTC in June 1999 is believed to be driving the current wind power plant building boom. Thus, legislative efforts to extend the PTC are a high priority for the U.S. wind industry.

The future of the U.S. market for utility-scale wind power is also influenced by the marketing of "green power," whereby electricity customers are offered the option of selecting environmentally preferred, but higher-cost sources for their electricity. These programs are under way in several regions of the country now, including some with encouraging customer support. It remains to be seen, however, if these programs will support a sustainable U.S. market for wind-generated electricity. Renewable energy advocates are also focusing on policies oriented toward the competitive power markets that will exist after restructuring. These initiatives aim to ensure that electric deregulation does not result in a generation mix based solely on lowest cost. A key initiative of the wind power community is to secure legislation for a renewables portfolio standard (RPS), which would require a certain percentage of electricity to be produced from renewable resources.

1.2 Industry Status

During the 1980s and early 1990s, Kenetech Windpower was a leading supplier of utility-scale wind turbines. However, an apparent combination of business and technical problems plunged the company into bankruptcy in 1997. The Kenetech turbines were not developed in partnership with DOE, but negotiations were under way at the time of their bankruptcy to jointly develop a new turbine. Currently, the only U.S. supplier of utility-scale wind turbines is Zond Energy Systems, the manufacturing subsidiary of Enron Wind Corporation. Zond offers turbines of 550- and 750-kW ratings and is currently completing installations of more than 200 MW using its 750-series turbine. While actual costs depend upon arrangements for each project, Zond's 750-series turbines appear to be competitive in both domestic and overseas markets.

Another U.S. turbine currently available is the AOC 15/50 (15-m diameter, 50-kW rating) by Atlantic Orient Corporation. Approximately 32 of these turbines have been deployed, some in remote locations. Another company, Northern Power Systems, offers turbines of 3 kW or less for integrated power systems, and it currently is developing a 100-kW turbine for extreme environments. Other U.S. manufacturers of turbines rated at 10 kW or less include Southwest Windpower, Bergey Wind Power, and World Power Technologies. Each of these companies is experiencing sales growth, but at the same time, they are interested in improving the cost effectiveness and reliability of their turbines and expanding their product lines.

1.3 Turbine Research Program

The Turbine Research Program, formerly called the Advanced Wind Turbine Program, was initiated by DOE in 1990 to assist U.S. industry in incorporating advanced technology into its wind turbine designs. The first phase of the program, Conceptual Design Studies, completed in 1992, identified and evaluated improvements to make existing wind turbines more competitive in the 1993–1995 time period. It also explored more advanced configurations that would be competitive for bulk-electricity generation in later years at sites having moderate wind speeds. Study results indicated that these advanced configurations were capable of achieving substantial improvements in performance, reliability and cost of energy (COE).

The second phase of the program, Near Term Product Development, involved the fabrication and testing of prototype turbines designed to produce electricity for \$0.05/kWh or less at 5.8 m/s (13 mph) sites. Those products were intended to bridge the gap between earlier technology and the "next-generation" of utility-scale turbines.

The third phase of the program, Next Generation Product Development, is in progress now. This phase stimulates U.S. industry to explore new concepts and apply cutting-edge technology to the development of prototype, utility-scale wind turbines. The objective is to produce electricity for \$0.025/kWh or less at 6.7 m/s (15 mph) sites. This third phase is a two-part process. In the first part, the Innovative Subsystems Project, DOE supports industry in developing and testing innovative components and subsystems. In the second part, the Next Generation Turbine Development (NGTD) Project, DOE assists industry in developing utility-scale, wind-turbine systems that might incorporate these innovations and other technology advancements.

NGTD is a two-stage project. The first stage, completed in 1997, was a Concept Definition Study intended to develop performance and cost estimates for the proposed systems, along with a work plan, budget, and schedule for the second stage of the project, Prototype Development. The following summary provides an outline of the NGTD development path.

Turbine Research Program

- Phase 1: Conceptual Design Studies
- Phase 2: Near Term Product Development
  - Part 1. Near Term Projects
  - Part 2. Value Engineered Turbines
  - Part 3. Near Term Prototype Testing
  - Part 4. Near Term Research and Testing
- Phase 3: Next Generation Product Development
  - Part 1. Innovative Subsystems Project
  - Part 2. Turbine Development Project
    1. Concept Definition Study
    2. Prototype Development

The Small Wind Turbine (SWT) project [1] was added to the Turbine Research Program in 1995 to stimulate the application of advanced technology in that portion of the industry that serves specialized markets requiring wind turbines in sizes from 5 to 40 kW. The goal of the SWT project is to assist U.S. industry in developing cost-effective, highly reliable small wind turbines for both domestic and overseas markets. The measure of merit for these systems, called the Cost/Performance ratio, is defined as the initial capital cost of the turbine divided by its net annual energy capture. This Cost/Performance ratio is very different than COE, which is related to life cycle cost. The SWT project objectives are to provide tested systems that achieve a Cost/Performance ratio of \$0.60 per annual kilowatthour or less at sites having annual average wind speeds of 5.4 m/s (12.1 mph), and to significantly reduce the COE by 2000.

2. SMALL WIND TURBINES

There was a time when thousands of small windmills generated electricity and pumped water in the United States. With widespread rural electrification, many turbines fell into disrepair and eventually were removed. In recent years, there has been a renewed interest in small wind turbines by farmers, ranchers, homeowners, and small businesses. Various incentives are offered to promote use. For example, 19 states permit net metering, which allows small power producers to sell excess electricity to the utility at retail prices. Also, the Emerging Renewables Buy-Down Program, sponsored by the California Energy Commission, is a four-year program offering rebates of up to 50% of the cost of grid-connected small wind turbines under 10 kW. In many cases, where the economics are not so favorable, wind turbine owners simply want to be independent of the grid or environmentally proactive.

DOE and NREL are involved in small wind turbine programs throughout the world, including village power applications in Argentina, Armenia, Bolivia, Brazil, Chile, China, India, Indonesia, Mexico, Philippines, and Russia. Half of the world's rural inhabitants, approximately two billion people, are without electric service. In remote regions of the world, there is an intense demand for energy, because even small amounts make a significant difference in lifestyle in applications such as lighting, small appliances, ice making, battery charging, and desalination.

The economics of small turbines is dramatically different than for utility systems. Nevertheless, good equipment which is properly marketed can generate substantial sales. For example, Southwest Windpower of Flagstaff, Arizona, sells its small battery-charging turbines in 45 countries. More than 24,000 units have been sold to date – 20,000 in the last four years – and the current sales rate exceeds 1,000 per month.

Three other companies, selected in a competitive procurement, are developing turbines under the SWT project. They will proceed in four stages, comprising (i) preliminary design of a prototype system, (ii) detailed design and qualification tests of key components, (iii) fabrication and field tests of the first turbine, and (iv) design refinement and qualification tests of the commercial prototype. These tests, of at least 1,000 hours, will be conducted at the National Wind Technology Center (NWTC). They will include IEC

1400-12 power performance and IEC 1400-11 acoustic emissions and loads tests. Documentation and testing will be a precursor to international certification.

The new turbines are highly integrated designs, with few moving parts, purpose-designed, variable-speed, direct-drive generators, and blades tailored for the particular generator characteristics. Manufacturers will provide complete systems, including electrical controls that can be integrated with photovoltaics and auxiliary generators. The major challenge in all cases is to maintain low capital-cost and high reliability.

All three turbines employ furling for overspeed control. The rotor is made to turn out of the wind by off-setting the center of thrust from the yaw or tilt axis. In this approach, it is important to avoid the "hunting" phenomenon, whereby the rotor moves into and out of the wind in response to unsteady aerodynamic and kinetic forces. This undesirable behavior causes noise emissions, loss of rotor efficiency, and potentially damaging cyclic loads. The mathematical modeling of this phenomenon is extremely difficult, so some development work is being done empirically.

2.1 WindLite Corporation

WindLite Corporation (WLC) was created in 1996 by several U.S. renewable energy experts who wish to address the emerging markets for clean, independent, electric power systems. Beginning in 2000, WindLite will manufacture both wind turbines and controllers. The turbines will be marketed as individual products and also as part of integrated power systems. The WLC 7.5-kW turbine, Figure 1, is being developed primarily as a battery-charging unit, although it also may be used in grid-connected systems. It is a three-bladed, upwind, variable-speed, direct-drive machine with a rotor diameter of 7 m. The wind turbine employs a wound-rotor generator and proprietary controller, the combination of which significantly improves its battery-charging efficiency. The projected Cost/Performance ratio for the WLC 7.5 is $0.46/kWh. The amount of the cost-shared NREL subcontract is $1,430,901.

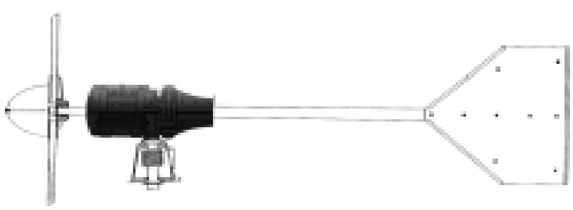

Figure 1. WindLite 7.5-kW variable-speed turbine.

WLC recently completed a two-phase truck test to assist in the design of the overspeed furling mechanism and provide data to validate analytical computer codes. The first phase of the test empirically determined the flow around the truck cab by driving the anemometer-arrayed vehicle down an airport taxiway. The second phase of the test will fill an extensive matrix of data regarding the steady-state and dynamic conditions of furling. The truck tests will not accurately represent the furling behavior in atmospheric conditions. However, they will be of considerable help in designing the furling mechanism for the WLC 7.5 turbine, because there are no validated methods for furling analysis of new turbines.

2.2 World Power Technology

World Power Technology (WPT), a privately owned business located in Duluth, Minnesota, has manufactured small wind turbines since 1978. The current product line includes six wind turbines ranging in size from 500 to 4,500 Watts. The new WPT Windfarmer, a 7-kW battery-charging turbine, is shown in Figure 2. It is a three-bladed, upwind, variable-speed machine employing a direct-drive permanent-magnet alternator. Fiberglass blades will be employed on a rotor approximately 5 m in diameter. The machine will use a unique, patented, angle-furling governor for protection in high winds. World Power is also developing a novel, counter-weighted, tilt-down tower of about 30 m height. The projected Cost/Performance ratio for the Windfarmer is $0.59/kWh. The amount of the cost-shared NREL subcontract is $1,248,838.

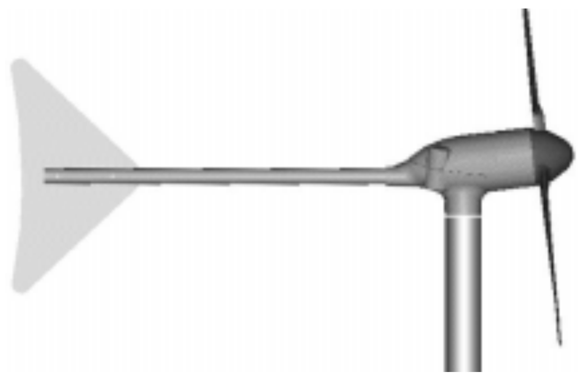

Figure 2. World Power 7-kW battery-charging turbine.

2.3 Bergey Windpower Company

Bergey Windpower Company (BWC) is a privately owned business operated in Norman, Oklahoma, since 1977. It has sold more than 1,800 turbines (0.85, 1.5, and 10 kW) in more than 80 countries since production began in 1980. The BWC Excel 40-kW turbine, which is targeted for battery charging in the village power market, is expected to be similar in appearance to the BWC Excel 10 in Figure 3. It is a three-bladed, upwind, variable-speed machine with a direct-drive permanent-magnet alternator. Blades are constructed of pultruded fiberglass in three rotor diameters for different wind regimes. The guyed-lattice tower will be offered in 36-, 55- and 82-m heights. Bergey is striving for a 5-year inspection interval, 10-year service interval, and 50-year operational life. The projected Cost/Performance ratio for the BWC Excel 40 is $0.38/kWh. The amount of the cost-shared NREL subcontract is $1,211,486.

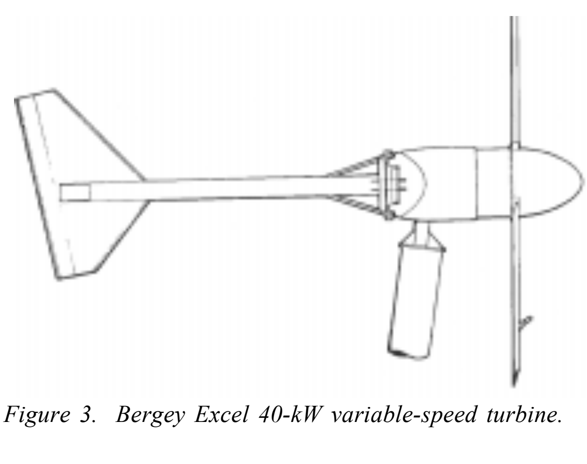

Figure 3. Bergey Excel 40-kW variable-speed turbine.

3. INTERMEDIATE-SIZE TURBINES

There is a class of wind turbines whose size is intermediate between the small systems described above and the grid-connected utility-scale systems. There are two such systems being supported by DOE.

3.1 Atlantic Orient Corporation

Atlantic Orient Corporation (AOC), in Norwich, Vermont, manufactures the AOC 15/50 turbine. The three-bladed, downwind machine with a 15-m rotor diameter has a 50-kW rating at a wind speed of 12 m/s (26.8 mph) and produces its peak power of 65 kW at 17 m/s (37.9 mph). It uses an integrated mainframe-drivetrain, Figure 4, which is fastened directly to the yaw bearing and tower top. Overspeed protection is by fail-safe, aerodynamic tip vanes supplemented by an electro-dynamic brake. To date, wood-epoxy blades have been used, although fiberglass blades are being considered by other prospective suppliers.

AOC has endeavored to make the turbine suitable for remote locations and extreme environments. Indeed, the machine is finding favor in the village power setting in remote areas where ease of transport and installation is desired. Thirty-two turbines have been deployed, some in remote areas of Alaska and Morocco. Several turbines are also installed in various research and test settings such as the NWTC, the U.S. Agricultural Research Center in Bushland, Texas, the Atlantic Wind Test Site on Prince Edward Island, Canada, and at Montana State University. The turbine also is the subject of round-robin testing in 1999 by NREL in the United States, Risoe National Laboratory in Denmark, and the Center for Renewable Energy Sources in Greece.

The AOC 15/50 was partially funded by NREL under the Near Term Product Development and Near Term Prototype Testing projects. The amount of these cost-shared NREL subcontracts is $1,793,594.

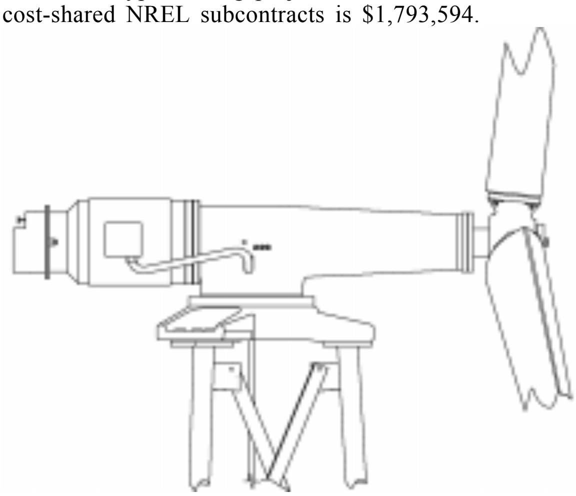

Figure 4. AOC 15/50 has been deployed in remote areas of Alaska and Morocco.

3.2 Northern Power Systems

The second of these intermediate-size turbines is the North Wind 100, manufactured by Northern Power Systems (NPS) of Waitsfield, Vermont, and developed in a collaborative venture with the National Aeronautics and Space Administration (NASA) Ames Research Center, the National Science Foundation (NSF), and DOE/NREL. The 100-kW, three-bladed, upwind, variable-speed machine, Figure 5, employs a direct-drive alternator developed under the Innovative Subsystems project noted above in Section 1.3. The wound-rotor salient-pole synchronous alternator was designed by Westinghouse Electric Company after extensive trade-off studies of competing architectures. The stall-controlled, 16.6-m rotor on the proof-of-concept turbine uses blades manufactured by LM Glassfiber. In developing the North Wind 100 specifically for remote and harsh environments, NPS draws on experience with its HR3 turbine deployed at the South Pole, where low maintenance and high reliability are design drivers.

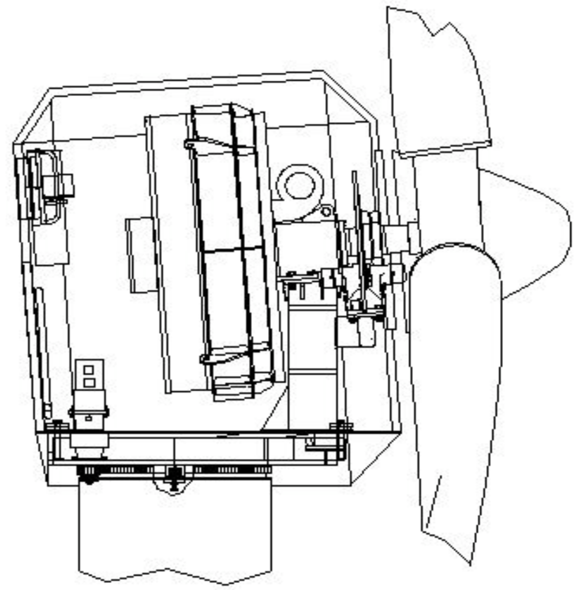

Figure 5. North Wind 100 cold-weather turbine.

The North Wind 100 proof-of-concept turbine was installed at the Vermont test site in December 1998. It is planned that a commercial prototype will be deployed for certification testing at the NWTC in December 1999, with follow-up development by NASA and NSF for applications in Alaska and the Antarctic. The cost-shared NREL subcontract amounts to $1,587,951. Follow-on work is likely to require additional funding.

4. UTILITY-SCALE TURBINES

A large part of the DOE/NREL development effort is being focused on turbines that will be deployed in 2000 and beyond. The process by which these turbines will evolve is as follows. First, the developers will fabricate and test a proof-of-concept (POC) turbine, the purpose of which is to demonstrate that the proposed next-generation turbine (NGT) is likely to achieve the project objectives. The POC turbine need not be identical in size to the NGT production prototype that will be demonstrated later in the project, but it is important that the POC turbine incorporate the technology, innovations, and design features that distinguish the NGT from other turbines of proven technology. Field tests of the POC turbine will be conducted in order to verify its operation, performance, loads and structural response, to validate analytical methods and predictive codes, and to obtain data that can be extrapolated to subsequent prototypes.

Using all of the information obtained in the POC field tests, subcontractors will repeat the design process described above and proceed with the fabrication and testing of an Engineering and Manufacturing Development (EMD) Turbine. The EMD turbine will be virtually identical in configuration and size to the NGT production prototype that will be demonstrated later in the project. It will be used to demonstrate structural integrity and dynamic stability, verify power performance and acoustic signature, refine control strategies, and develop assembly, installation, maintenance, and safe operating procedures. The EMD turbine will also be used as a vehicle to refine analytical methods and predictive codes, to develop and test component improvements, to develop manufacturing methods, and to generally improve the cost-effectiveness of the design.

Using all of the information obtained in the EMD field tests, the developers will repeat the design process described above and proceed with the fabrication and testing of the NGT production prototype. The NGT turbine is intended to be the definitive product resulting from the NGTD project. The developers will conduct comprehensive field tests, including the demonstration of certain safety, performance, and reliability criteria. Emphasis will be placed on compliance with IEC standards and certification of the turbine by a recognized international agency.

The objective of the NGTD program is to develop wind turbines that are capable of generating electricity for \$0.025/kWh or less. To understand the importance of this goal requires a brief look at the U.S. electricity market and at projections for future electricity prices.

4.1 Electricity Sales, Generating Capacity, Prices

Historically, the demand for electricity has been related to economic growth. The Energy Information Administration (EIA) of DOE predicts in its *AEO99* report [2] that this positive relationship will continue, but the magnitude of the ratio is uncertain. Electricity demand in the residential, commercial, and industrial sectors is projected to grow by 1.6%, 1.4%, and 1.1% a year, respectively, between 1997 and 2020.

Around 363 GW of new generating capacity will be needed by 2020 to meet growing demand and replace retiring units. Between 1997 and 2020, 50 GW (51%) of current nuclear capacity and 76 GW (16%) of current fossil-steam capacity are expected to be retired. This reduction in baseload capacity has a marked impact on the electricity outlook after 2010.

Before building new capacity, utilities are expected to use other options to meet demand – existing plants, power imports, and purchases from cogenerators. Even so, more than 1,210 new electricity generation and co-generation plants, with average plant capacity of 300 MW, will be needed by 2020 to meet growing demand and offset retirements. Of the new capacity, 88% is projected to be combined-cycle or combustion turbine technology, 9% is new coal-fired capacity, and 3% consists of renewable technologies – primarily wind and biomass gasification units. Each percentage point increase in the assumed economic growth rate of 2.1%, as measured by the gross domestic product, leads to a 17% change in demand in 2020, corresponding to a difference of 124 GW of new capacity required.

There are a growing number of state programs in support of renewable energy investment, and proposed federal legislation for renewable portfolio standards (RPS) are similar to those included in the state restructuring plans. Essentially, these proposals specify that a percentage of the electricity generated or sold must be produced by qualifying renewable power plants, which include all renewable facilities other than hydroelectric and municipal solid waste. The RPS would have an impact on the types of plants built to meet the growing demand for electricity, and new wind plants are expected to make key contributions.

The long-term implications of mandates, renewable portfolio standards, green power marketing, system benefit funds, and other government actions are not entirely clear, but they are having an immediate effect of increasing renewable generating capacity. And almost 64% of this known new capacity is from wind. The combination of government actions, technology improvements, and lower costs could boost wind-powered generating capacity above 20 GW by 2020, as the EIA found in analyzing the "high renewables case" depicted in Figure 6.

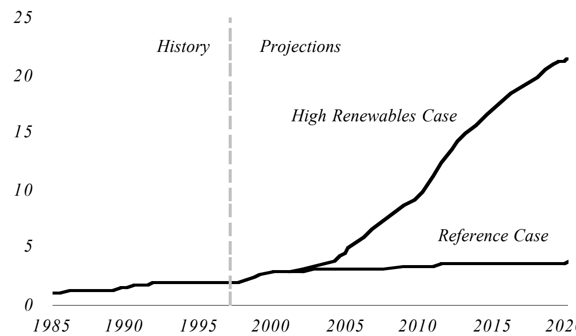

Figure 6. Wind-powered electricity generating capacity in the years 1985-2020 (GW).

Many people believe that wind energy is at a disadvantage because of its higher costs compared to fossil-fueled generation. Between 1997 and 2020, the average price of electricity in real 1997 dollars is projected to decline by almost 1% a year as a result of competition among electricity suppliers. Projected prices in 2020 are 16% to 22% lower than 1997 prices. Although natural gas prices are projected to increase, they are offset by declining coal prices, declining capital expenditures, and improved efficiencies for new plants. Furthermore, retail competition is expected to lower electricity prices as a result of the transition to competitive pricing in five regions – California, New York, New England, the Mid-Atlantic Council (Pennsylvania, Delaware, New Jersey, and Maryland), and the Mid-America Interconnected Network (Illinois, Wisconsin, and Missouri).

Table 1. Costs of electricity from new plants.

	2005		2020	
	Conventional Pulverized coal	Advanced combined cycle	Conventional Pulverized coal	Advanced combined cycle
	1997 cents per kilowatthour			
Capital	2.50	0.69	2.55	0.65
O & M	0.33	0.20	0.33	0.20
Fuel	1.10	2.16	0.98	2.40
Total	3.92	3.06	3.84	3.25

Technology choices for new generating capacity are made to minimize cost while meeting local and federal emissions constraints. The EIA forecasts contained in *AEO99* take into consideration the cost and performance characteristics of new plants, the fuel costs, and the captial recovery requirements. Table 1 presents the results of an EIA analysis indicating that the lowest cost per kWh of electricity will be from advanced combined-cycle (natural gas) plants – 3.06 cents in 2005 increasing to 3.25 cents in 2020. The cost of producing electricity from new coal-fired plants is expected to be slightly higher.

4.2 Cost of Energy Target

The *AEO99* report forecasts the need for a significant amount of new electricity generating capacity in the next two decades, and it identifies the lowest-cost source as advanced combined-cycle plants generating at approximately \$0.03/kWh. This, it would seem, establishes the COE at which renewables must compete in an unregulated, unsubsidized market.

To compete successfully against established technology, with its entrenched industrial, political, and financial infrastructure, wind-generated electricity may need to demonstrate a compelling cost advantage. This may also be said of the ability of U.S. manufacturers to compete against established European companies with proven products and financial capabilities. Therefore, in setting its COE objective of \$0.025/kWh, the DOE established an aggressive target intended to facilitate market entry of the next-generation turbines.

The method by which COE is calculated is subject to interpretation and circumstance, but for the purpose of making relative comparisons among turbines, DOE and NREL use the following equation [3]. COE is the life-cycle cost-of-energy, in January 1997 dollars, calculated for a 50 MW (rated) wind plant with an expected life of 30 years. Annual energy capture is calculated for a site having a 6.7 m/s annual average wind speed at a height of 10 m, a Rayleigh distribution, and a vertical wind-shear exponent of 0.143. The turbine manufacturing volume is assumed to be 50 MW (rated) capacity per year, assuming prior production of 150 turbines.

$$\mathrm{COE} = \frac{(\mathrm{FCR} \times \mathrm{ICC}) + \mathrm{LRC}}{\mathrm{AEP}} + \mathrm{O\&M}$$

COE ≡ Levelized Cost of Energy (\$/kWh)

FCR ≡ Fixed Charge Rate (1/yr) = 0.1056

ICC ≡ Initial Capital Cost (\$)

LRC ≡ Levelized Replacement Cost (\$/yr)

AEP ≡ Annual Energy Production (kWh)

O&M ≡ Annual Maintenance Cost (\$/kWh)

4.3 Reducing the Cost of Energy

A technical breakthrough in wind turbine design is not expected. Rather, a number of factors must coalesce to achieve this aggressive COE objective. These factors are not limited to innovative wind turbine architecture, but also include serial production, value engineering, and improved engineering and manufacturing methods. For example, Quarton [4] observes that the sophistication of the analytical methods used as the basis of wind turbine design has increased enormously over the last 20 years. He sites specific examples of improved engineering methods with regard to the modeling of turbulent inflow, structural dynamic response, and power train and control systems. Moreover, there has been a transition of these methods from research codes to design tools, which has enabled engineers to move down the path of optimization even before turbines are fabricated and tested. Additional advancements have been made in determining extreme loads by statistical analysis [5], using solid modeling programs in early stages of design, linking solid modeling with finite-element stress analyses, and adapting multi-axial stress analysis computer codes to the wind turbine design problem. There have also been significant advances in the laboratory testing of wind turbine components, such as gearboxes and blades, to better determine their lifetimes. If it is discovered that excess design margins exist, materials may be removed to achieve weight and cost reductions.

Aerodynamicists now have a better understanding of unsteady flow, post-stall behavior, and the impact of airfoil and planform geometry on roughness losses and acoustic emissions. Not long ago, it was considered innovative to use special-purpose airfoil families such as the NREL series, on the AOC 15/50, AWT-27, and Z-40 turbines. For current designs, special-purpose airfoils are developed for each turbine, as is the case for the Bergey, World Power, and WindLite turbines.

Manufacturing improvements, particularly for turbine blades, have developed in parallel with design improvements. They have focused on lower cost and better quality from advanced composite fabrication methods such as resin infusion molding and improved root attachments.

There is much to be said for the profound impact on cost of purposeful design evolution, sometimes called value engineering, in which engineers have the opportunity to evaluate loads and stresses, learn from past mistakes, incorporate new technology, consolidate or eliminate parts, and generally modify their products to improve reliability and reduce cost. DOE and NREL have supported several such efforts in their advanced wind turbine programs.

Once suppliers have developed a serial production capability and are able to respond to increasing competition, there is a trend toward decreasing costs. Volume production allows them to reduce unit costs, and it improves the opportunity for competitive source-selection of vendors. The aggregate effect of these factors is demonstrated by the cost trends of Reference [6], where a 45% reduction is shown over a 7-year period (1990 – 1996) for turbines of 32- to 45-m rotor diameter. Similar trends are expected for larger turbines of 45- to 72-m rotor diameter, which initially have demonstrated higher costs/kWh than the earlier turbines.

There are many factors at play in the drive to reduce the cost of wind-generated electricity. Some of the most exciting are the design innovations that are currently being developed. These include

- direct-drive generators to improve efficiency and reliability by eliminating gearboxes
- power electronics for variable-speed operation and rotor torque control
- low-stiffness (flexible) towers to reduce weight and allow higher hub heights
- advanced controls, such as individual blade pitch, for loads mitigation
- highly integrated structures to minimize parts
- optimized foundations and towers to reduce weight and cost
- flapping rotors to reduce system loads

- improved aerodynamic efficiency through better airfoil and planform design
- aeroelastically-tailored blades with bend-twist coupling to increase energy capture
- low-stiffness (flexible) blades of low solidity to shed loads and reduce rotor weight.

Advanced rotor designs provide the greatest potential for COE reduction. This is easily understood in view of the fact that, typically, the rotor accounts for 25% of turbine capital cost, 90% of the loads applied to the structure, and 100% of the energy capture. As an example of what can be accomplished, the benefit of blade structural flexibility is demonstrated in Figure 7 [4], which shows a significant reduction in blade flapwise loading of the Carter 300 turbine in comparison to calculations for rigid-blade turbines with and without pre-cone. These reduced loads should result in lighter structures. In combination with improved manufacturing and state-of-the-art aerodynamic design, the expected result is a noticeable improvement in COE.

The challenge facing wind turbine designers is to identify these cost-reduction opportunities and incorporate them in the next-generation turbines. We understand that this endeavor is accompanied by large technical and business risks, and that success is not assured. For this reason, DOE has entered into long-term development contracts in which it supplies approximately 70% of the required funding. In addition, the National Renewable Energy Laboratory and Sandia National Laboratories provide design review, analysis, and test support to these subcontractors.

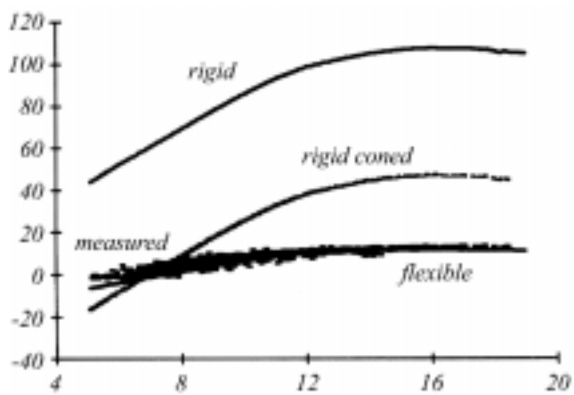

Figure 7. Carter 300 steady-state, blade-root flapwise bending moment (kNm) vs wind speed (m/s).

4.4 Zond Energy Systems

Zond Energy Systems has its engineering and manufacturing facilities in Tehachapi, California. Its first turbine development project with DOE/NREL was the Value Engineered Turbine that resulted in the 550 kW Z-40, of which 93 are installed in China, Greece, Ireland, Korea, Mexico, and the United States. Zond's next turbine, the 750-kW Z-46, was not developed under subcontract to DOE/NREL, but there was collaboration in design review, analysis support, and certification testing. In expanding its 750-series turbines beyond the Z-46, Zond introduced Z-48 and Z-50 turbines. The three models are certified by Germanischer Lloyd for 30-year life in IEC Class I, Class II and Class III sites, respectively. There are 203 of the 750-series turbines in California, Iowa, Minnesota, and Nebraska; 462 turbines are under construction.

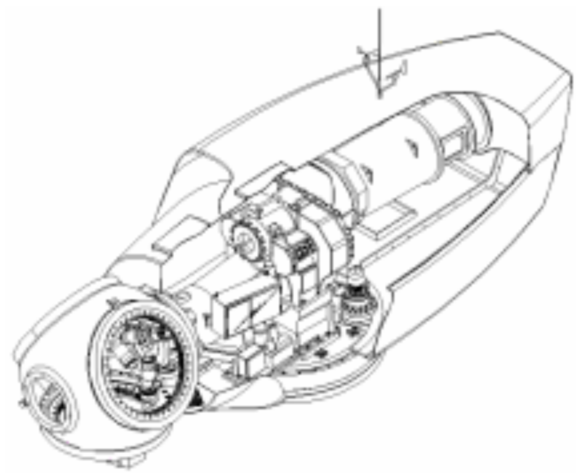

Figure 8. Zond 750-series variable-speed wind turbine.

The 750-series turbines illustrated in Figure 8 are three-bladed, upwind, variable-speed machines, either on free-standing tubular or lattice towers. In July 1998, Zond entered into a Near Term Research and Testing subcontract with NREL. The goal is to develop engineering improvements that will lower the cost and improve the performance and reliability of the 750-series turbines, with the objective of achieving significant reductions in the COE. Zond's efforts will focus on value engineering of the hydraulic, yaw, and electrical-control systems along with new engineering initiatives in individual blade-pitch control, low-stiffness towers, and advanced blade manufacturing methods. A prototype of the NTRT turbine will be installed at Zond's Tehachapi site to conduct component qualification tests, and eventually, system tests in support of certification. Results to date indicate the NREL/Zond NTRT project will result in a large reduction in COE over the earlier Z-46 turbines. The cost-shared NREL subcontract amounts to $8,331,344.

A separate development effort was undertaken by Zond when it entered into a Next Generation Prototype Development subcontract with NREL in June 1997. Current thinking has this turbine rated in the range of 1.5 to 2 MW, but its architecture has not been finalized. Direct-drive generators are being considered, along with conventional gearboxes. Significant departures from conventional rotor design are anticipated, including purpose-designed airfoils and low-solidity, flexible blades with individual pitch control. Taller, low-stiffness towers are expected, as are control strategies to optimize energy capture and mitigate loads. Zond expects to finalize design and begin construction of a proof-of-concept turbine in 1999. The cost-shared NREL subcontract amounts to $20,844,761.

4.5 The Wind Turbine Company

The Wind Turbine Company (WTC) of Bellevue, Washington, which is fairly new to the DOE/NREL Turbine Research Program, was awarded one of NREL's Next Generation Prototype Development subcontracts in January 1997. WTC's proposed technical approach typifies lightweight, two-bladed, downwind machines in contrast to heavier, three-bladed, upwind machines.

WTC's vision of its megawatt-scale WTC 1000 turbine includes purpose-designed blades with individual pitch control, a variable-coning (flapping) rotor, highly integrated structure and drivetrain, loadmitigating control strategies, consolidated fluid systems, and a very tall (100-m) guyed tower. Considering the aggressive technology suite being pursued, DOE and NREL view this as a high-risk project. On the other hand, it may be necessary to assume this level of risk to achieve the aggressive $0.025/kWh COE objective. The WTC 1000 is targeted for wind power plant applications, principally in Mid-western states, and current projections show that it will meet the COE objective.

The WTC project is a good example of the improved engineering methods being used in turbine development. For structural-dynamic analysis, advanced simulation codes are being used by Windward Engineering in the United States while advanced versions of distinctly different codes are being used in parallel by Garrad-Hassan in Britain. WTC makes extensive use of a solid modeling code in structural and mechanical design. It is an excellent tool for visualizing and manipulating the configuration. It provides accurate component weights, even in the early stages of design, and is used as a pre-processor to develop batch files for finite-element stress analysis. Figure 9, which shows a chassis-mainframe designed using this technique, also illustrates the strategy of highly integrated turbine components. In other engineering activities, WTC is employing statistical methods for extreme loads extrapolation, evaluating multi-axial fatigue for components loaded non-orthotropically, and using highly refined metallurgical and manufacturing processes to minimize weight and improve reliability.

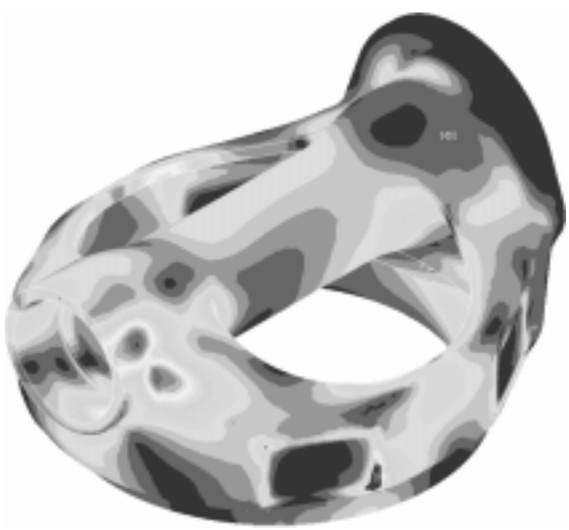

Figure 9. Highly integrated WTC part designed with linked solid-modeling/finite-element codes.

The WTC 250 proof-of-concept turbine, illustrated in Figure 10, is configured to facilitate the testing of various design alternatives, such as fixed- or variable-speed operation, pitch-to-feather or pitch-to-stall, and varying amounts of yaw damping or driving torque. The WTC 250 will use a 40-m free-standing tubular tower, and a 33-m rotor with blades manufactured by Rotorline. First rotation is scheduled for Fall 1999 at the NWTC, where it will be tested for at least one wind season before design optimization proceeds. The amount of the cost-shared NREL subcontract is $22,136,146. The project is also supported by a $950,000 contract with the California Energy Commission.

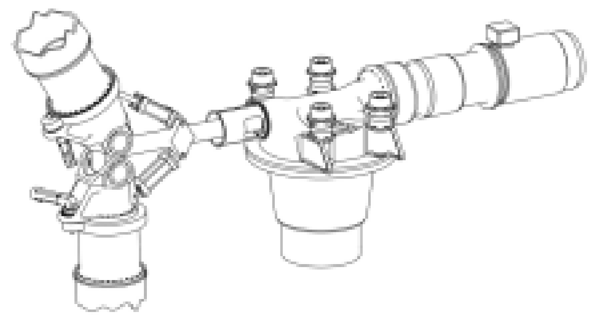

Figure 10. WTC 250-kW proof of concept turbine shown with its nacelle removed.

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